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Research Article
Sub-surface Analysis When Finish Turning Inconel 718 High Speed Machining with Minimum Quantity Lubrication (MQL)

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Abstract
The Minimum Quantity Lubrication (MQL) is an environmental friendly lubrication method in metal cutting industries where a very small amount of vegetable oil or biodegradable synthetic ester is sprayed close onto the cutting edge with compressed air. When employed, the usage of the dangerous cutting fluid may possibly be eliminated. This study reports sub-surface analysis of Inconel 718 when finish turning with coated carbide tool TiAlN (PVD) under high speed machining with MQL and dry cutting conditions. The microstructure analysis on the machined surface suggests that plastic deformation has taken place, leading to severe deformed layers of microstructure alteration at the subsurface level. Work hardening under the machined surface was evident from the micro-hardness measurements where higher hardness was measured near the surface and decreases to the bulk material hardness value deep into the subsurface. The results of the experimental study show that machining process and tool wear conditions influence the severity of the deformed layer and micro-hardness value.

Key words: Biodegradable synthetic ester, MQL, carbide tool TiAlN, micro-hardness

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Almost all of the mechanical energy in machining Inconel 718 is converted to heat and this causes high temperature along the cutting edge. The rate of the energy conversion depends on the machining parameters such as cutting speed, feed rate and depth of cut. High cutting speed requires more energy and produces more thermal energy and thus increases the temperature in the cutting zone. The situation is even worse when cutting metal with low thermal conductivity such as Inconel 718. Heat localization close to the cutting edge of the tool always occur when machining[1] Inconel 718. It is estimated that almost 80% of the heat concentrated at the cutting edge and the rake face which helps accelerate tool failure[2]. Another disadvantage of machining Inconel 718 is Build-Up Edge (BUE). When machining Inconel 718, BUE sticks between the tool and the workpiece interface, this encourages the destruction of the workpiece surface integrity[3]. With poor surface integrity, the usage of this material in high temperature applications increases the risk of failures. Thus, cutting Inconel 718 is not only causes short tool life due to the heat but also results in poor surface integrity due to BUE[4]. Therefore, Inconel 718 is always considered as highly complex material to be machined[5]. Numerous investigations confirm that quality of the machined surface suffers severe damages by fatigue, creep and stress cracking and thus compromised surface integrity requirements[6].

This study presents the results of a subsurface analysis when finish turning Inconel 718 using PVD coated TiAlN carbide tool at high cutting speed under MQL and dry cutting conditions. The objectives of this experimental study are to determine the effects of these cutting conditions on the subsurface micro structure integrity of Inconel 718 namely, the machined workpiece microstructure alteration and micro-hardness.

MATERIALS AND METHODS

In this experiment, Inconel 718 was finish-turning with COLCHESTER T4 6000 CNC Lathe fitted with UNIST MQL delivery system as shown in Fig. 1. The cutting process is carried out using single layer PVD coated TiAlN carbide cutting tool (CNMG120408). The MQL cutting fluid is sprayed using three external tubes. The nozzles are directed to the main shear zone (zone A), the secondary shear zone (zone B) and the clearance face zone (zone C) to increase the effectiveness of the cutting fluid[7].

The chemical composition of the as-received work piece is given in Table 1 showing all the three main components,

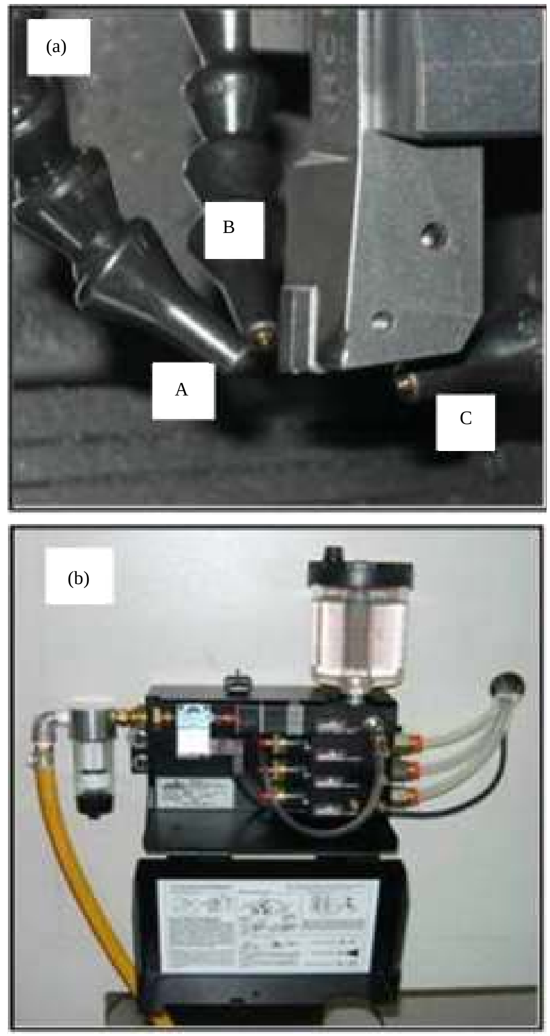

Fig. 1(a-b): UNIST MQL system (a) Nozzle arrangement and (b) MQL system

nickel (Ni), chromium (Cr) and ferum (Fe), along with all other components that make up Inconel 718. The machining parameters are shown in Table 2 with dry cutting is denoted as MQL 0 mL h^{-1}. The work piece was pre-machined to remove any defect that would interfere with the experiment results using designated tool at the beginning of each run.

At the end of each run, a sample of the machined workpiece was collected and a segment of the sample was mounted onto hot-press bakelite mould. The prepared sample was ground and polished using semi-automatic polishing unit. The rough grounding was performed on wet metallographic grinding paper of grit 240, followed by 400, 800 and finished with grit 1200.

Finally, the specimen was polished with 9 llffi, followed by 6 11 m and finally with 1 11 m polycrystalline diamond

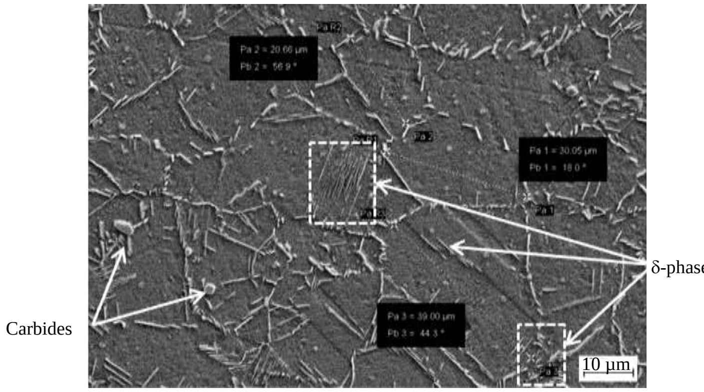

Fig. 2: Microstructure of the as-received Inconel 718

Table 1: Chemical Composition of Inconel 718 (wt%)

Ni	Cr	Fe	Nb+Ta	Nb	Mo	Ti	Al	Si	C	Mn
53.59	18.19	18.03	5.30	5.30	3.03	0.94	0.60	0.09	0.05	0.05
Co	Mg	Cu	Ca	P	B	S	Ta	Bi	Pb	Se
0.04	0.0025	0.020	<0.010	0.007	0.004	0.001	0.001	<0.0001	<0.0001	<0.0001

Table 2: Machining parameters

	Level		
Factors	1	2	3
x1- Cutting speed, V (m min^{-1})	90	120	150
x2- Feed rate, f (mm rev^{-1})	0.10	0.15	-
x3- Depth of cut, d (mm)	-0.30	0.50	-
x4- MQL flow rate, V (mL h^{-1})	0	50	100

suspension to obtain mirror-like surface. Later, the sample was etched using killing agent[8], then viewed and photographed under optical microscope and SEM.

The as-received microstructure of workpiece is shown in Fig. 2. The image was captured usmg Scanning Electron Microscope (SEM) at 1000xg magnification. The as-received microstructure shows carbides and needle-like o phase. Needle-shape o-phase are clearly visible along the grain boundaries, however, y' and y" precipitates are not visible because they are too small to be viewed using SEM[9]. The average grain size was measured at 28 llffi.

Subsurface micro-hardness of the machined samples were measured using Shimadzu DUH-W201S normal to the machined surface. Micro-hardness measurements were carried out using 200 g (about 2 N) vickers indenter loaded. Two hundred grams indenter was selected after taking into account the size of the indention that it will create on Inconel 718 surface, which is normally around 30 urn in diagonal length. The micro-hardness were measured up to a depth of1500 µm, allowing spacing of around 50 µm between the readings. Three measurements were taken at every depth for all samples.

RESULTS AND DISCUSSION

Microstructure changes: Figure 3 shows the microstructure image obtained from a sample of dry experiment at cutting speed of 90 m min^{-1}, feed rate of 0.15 mm rev^{-1} and depth of cut 0.50 mm, whilst Fig. 4 shows the microstructure image obtained from a sample of MQL 50 mL h^{-1} experiment at cutting speed of 120 m min^{-1}, feed rate of 0.10 mm rev^{-1} and depth of cut 0.50 mm. From these images, plastic deformation has taken placed especially on the top layer closest to the machined surface (close-up image). The plastic deformation is in the form of grain distortion in the direction of feed rate. The effects of severe thermal and mechanical pressure on the machined surface during machining process have resulted in elongated shape grain boundaries from it initially round-cornered shape.

When Fig. 3 and 4 are compared, microstructure changes in Fig. 3 appear worse than that of Fig. 4. The grain boundaries in Fig. 3 are more elongated and compressed than the grain in Fig. 4 although, the cutting speed is higher than that of Fig. 3. This observation indicates that the presence of cutting fluid somehow has affected the microstructure. It is also obvious from Fig. 3 and 4 that the rate of distortion reduces as the depth of the subsurface increases. Less effect on the grain boundaries was observed for both images as the depth increases.

Figure 5 compares microstructure obtained from samples of dry, MQL 50 and 100 mL h^{-1} experiments at 150 m min^{-1} with a feed rate of 0.10 mm rev^{-1} and depth

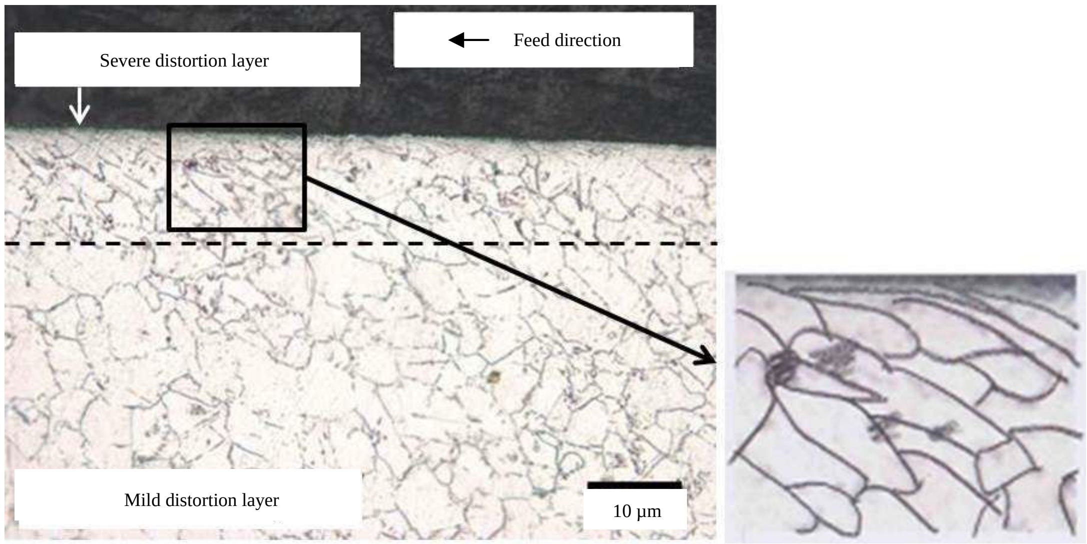

Fig. 3: Microstructure under dry condition at cutting speed of 90 m min^{-1}, feed rate of 0.15 mm rev^{-1} and depth of cut 0.50 mm

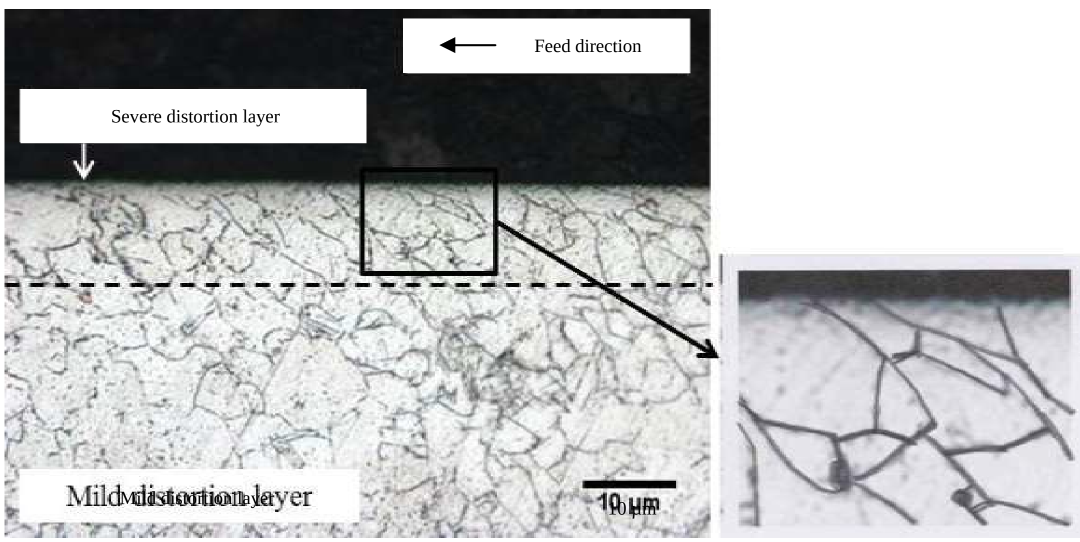

Fig. 4: Microstructure under MQL 50 mL h^{-1} condition at cutting speed of 120 m min^{-1}, feed rate of 0.10 mm rev^{-1} and depth of cut 0.50 mm

of cut of 0.50 mm. Microstructure changes were indicated using strain angle. Larger strain angle indicates greater microstructure distortion. At high speed of 150 m min^{-1}, the strain angle between MQL 50 and 100 mL h^{-1} is almost comparable. A closer look at the conditions of the grain elongation shows that the microstructure changes in MQL 100 mL h^{-1} are more severe where the grains are thinner and compressed when compared with that of MQL 50 mL h^{-1}. At high speed with blunt tool, temperature and mechanical stress are very high, resulting in severe distorted microstructure[10]. Greater distortion in the sample of MQL 100 mL h^{-1} is mostly likely due to the present of the MQL fluid. When material at high temperature during machining process encounters spray of MQL fluid with compressed air at about 23°C, a sudden thermal shock similar to quenching process occurs. As a result, extreme strain hardening took place and together with the cutting and rubbing process led to greater distortion.

On the other hand, similar effect of quenching did not seem to occur with the MQL 50 mL h^{-1} condition. This is may be due to insufficient amount of fluid in the MQL 50 mL h^{-1} to reproduce similar quenching effect. In the earlier discussion, the result of microstructure changes for cutting speed of 120 m min^{-1} under MQL 50 mL h^{-1} condition shows that the

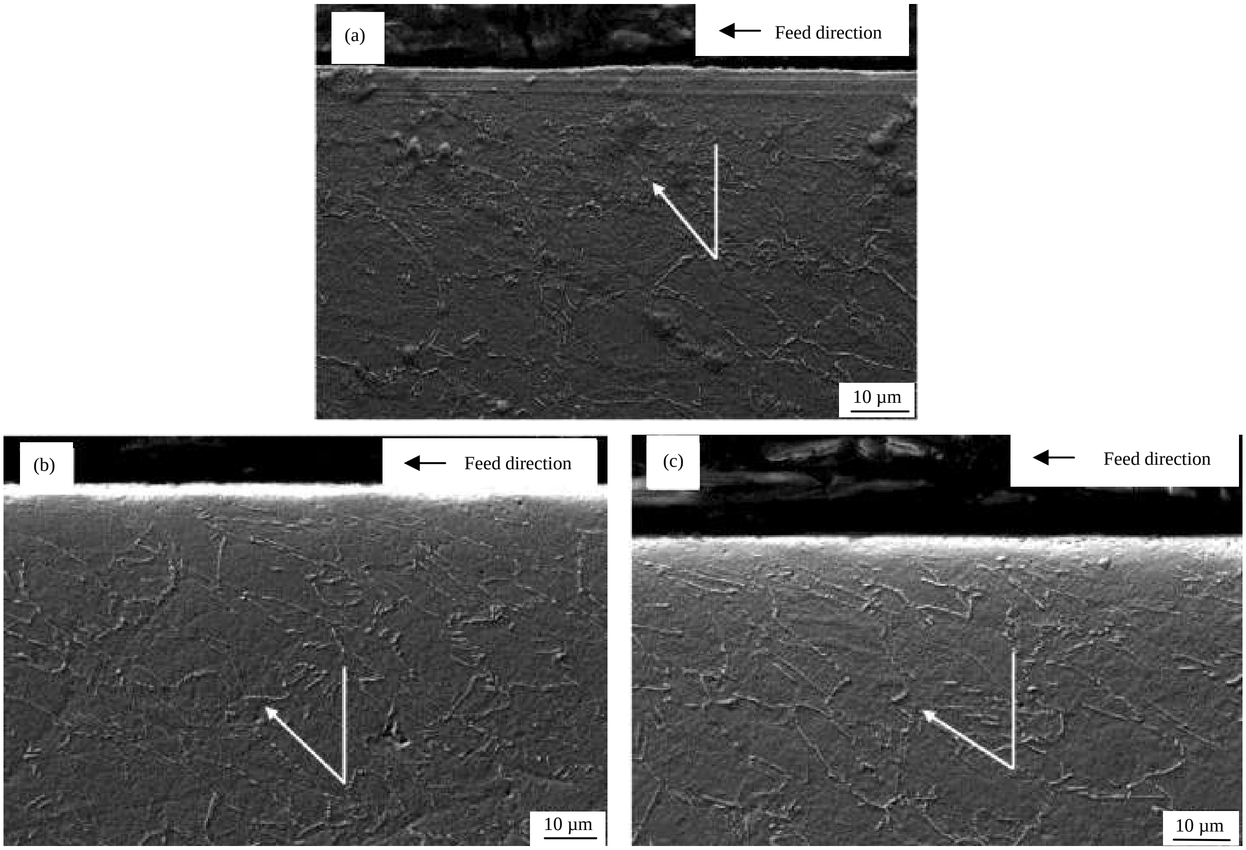

Fig. 5(a-c): Effect of cutting conditions on microstructure at cutting speed of 150 m min^{-1}, feed rate of 0.10 mm rev^{-1} and depth of cut 0.50 mm, (a) Dry, (b) MQL 50 mL h^{-1} and (c) MQL 100 mL h^{-1}

presence of MQL fluids slow down microstructure changes. This observation may infer that high volume of MQL fluid may not be suitable for high cutting speed where dry conditions are more likely perform better. When Fig. 5a and b are compared, there are incomparable. Although, Fig. 5b looks worse than Fig. 5a in term of microstructure changes, but the elongation orientation and the grain sizes look alike.

The effect of tool wear at different cutting time during machining process on microstructure changes is shown in Fig. 6. At the beginning of the process, the sharp tool did not show any effect. When the wear increased at t = 0.50 min, there is a small effect as shown by the small strain angle on Fig. 6b. At t = 1.50 min, a larger strain angle was observed on Fig. 6c. Observation on Fig. 6a-c evidently shows that as tool wear increased, the grain distortion and orientation becoming worse. The effect of tool wear was evident on the microstructure alteration. This increased in strain angle indicates a greater distortion effect, as a result of higher cutting pressure from the blunt tool. Figure 6c and d compares distortion effect between dry and MQL 50 mL h^{-1} experiment. Strain angle from Fig. 6d shows a smaller distortion effect which explained the slightly low pressure impact on the workpiece when using MQL 50 mL h^{-1} as compared to the dry method[11]. It has been established that tool wear depends largely on the cutting temperature. Strain angle difference in Fig. 6c and d suggests that there might be a possibility that cutting temperature may also cause microstructure alteration.

Haron *et al.*[12] in their surface integrity study on AISI hardened steel claimed that compressed and distorted effects on the microstructure was caused by heat at high speed cutting of 160 m min^{-1}. No compressed and distorted effects were observed when cutting at lower speed of 80-140 m min^{-1}. Apart from that, Fig. 6b and c also suggests that the conditions of the tool wear were partly linked to the distortion effect. When the wear rate increases, the tool starts to blunt and causes smaller relief angle which lead to greater surface contact between the tool and the workpiece and this put additional effect of rubbing which increases the friction[2].

Pusavec *et al.*[13] in their study on the effect of various cooling techniques on machining Inconel 718 did not observe any microstructure changes at 60 m min^{-1}. In their study, the

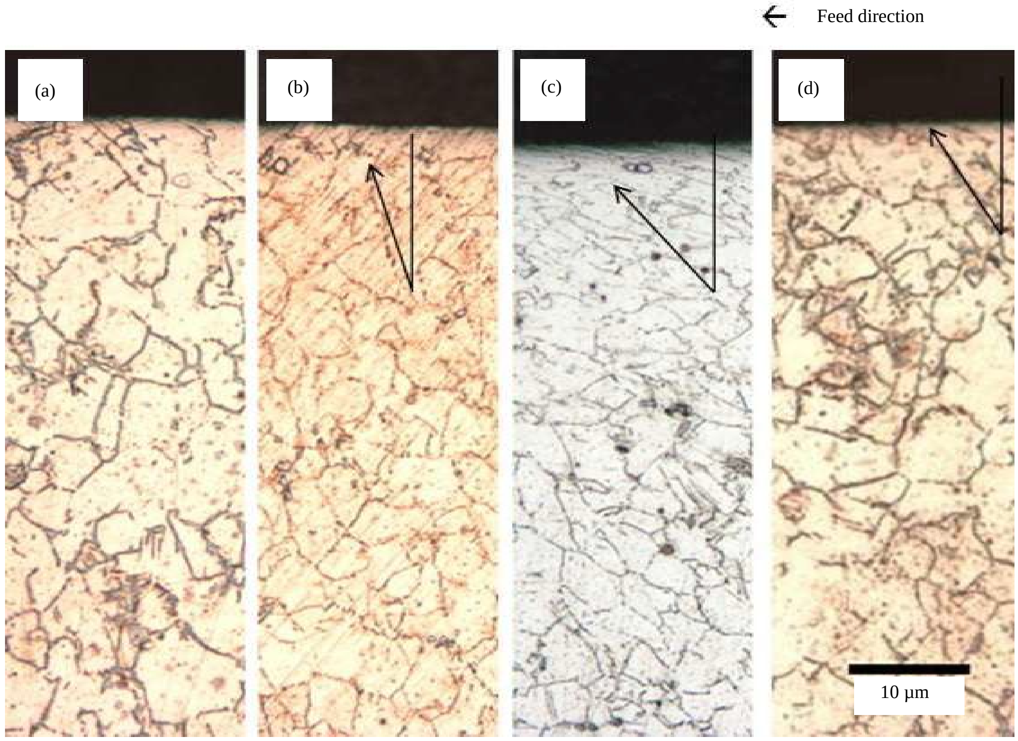

Fig. 6(a-d): Microstructure at different cutting time for cutting speed of 150 m min^{-1}, feed rate of 0.15 mm rev^{-1} and depth of cut 0.50 mm, (a) Bulk, (b) t = 0.50 min dry, (c) t = 1.50 min dry and (d) t =1.50 min MQL 50 mL h^{-1}

cutting was very short. The tools did not have any wear at all because of short cutting time. With a sharp tool condition, the pressure applied to the workpiece is not as extreme as a blunt tool, therefore sharp tool had no impact on the microstructural changes. Short cut also does not give sufficient time for the thermal and mechanical effects to take effect on the workpiece for distortion to occur. This experimental result shows that continuous prolonged pressure together with wear condition of the cutting tool causes plastic deformation.

Continuous cutting increased cutting temperature up to 900°C when machining Inconel 718, as reported by Itakura *et al*.[14] and Xue and Chen[15]. High temperature condition when machining low conductivity workpiece such as Inconel 718 causes heat localisation, thus making the condition even worst[13]. Figure 6, severe microstructural changes occurred within the top 10 µm, smaller grain size was observed with narrow elongated grains, distorted towards the feed direction. Although, the severely distorted layer looks shallow, yet microstructural changes are still visible to the bottom layer of Fig. 6, at the depth of close to 50 µm. On technical deficiency, observation for deeper distortion was not possible to observe the effect up to a depth of 500 µm, in line with the results of the micro-hardness. Furthermore, the elasticity of Inconel 718 at 900°C is 134 GPa, which is much lower than that of carbon steel which is at 207 GPa, therefore the effect of the distortion is much more severe in Inconel 718 compared to other alloy materials. In this experiment, the microstructure deformations and slip in the grain boundaries resulted in elongation of grain indicates severe plastic deformation has taken placed due to high thermal and mechanical effect at high cutting speed.

Micro-hardness: In this experiment, all samples indicate that work hardening occurred during machining process. The measured micro-hardness from the surface of the machined surface was all higher than that of the initial bulk material. The hardness was found to decrease until to a value of around 280 HV as the depth increased. No softening effect took place on the machined surface of Inconel 718 in this study although some earlier studies show that it occurs due to over-aging[16].

Figure 7 compares micro-hardness readings taken from samples of dry, MQL 50 and 100 mL h^{-1} at 150 m min^{-1} with a feed rate of 015 mm rev^{-1} obtained in this study. From this observation, sample from MQL 100 mL h^{-1} indicates a high measurement of micro-hardness at the machined surface at 480 HV when compared to dry and MQL 50 mL h^{-1}. Based on this result, it seems like the severe effects of high thermal and pressure on the microstructure changes has translated

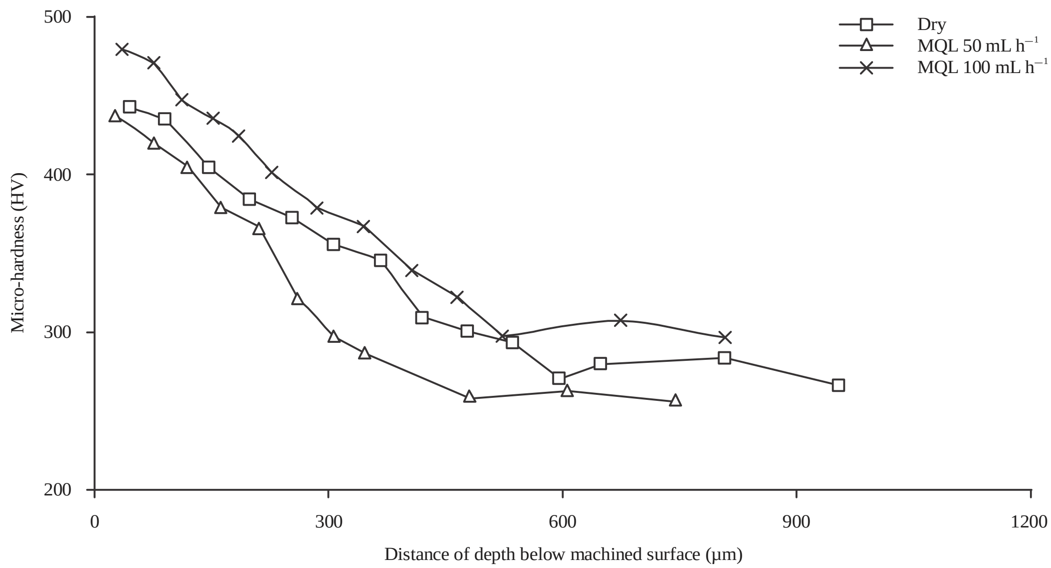

Fig. 7: Micro-hardness at cutting speed of 150 m min^{-1}, feed rate of 0.15 mm rev^{-1} and depth of cut of 0.50 mm

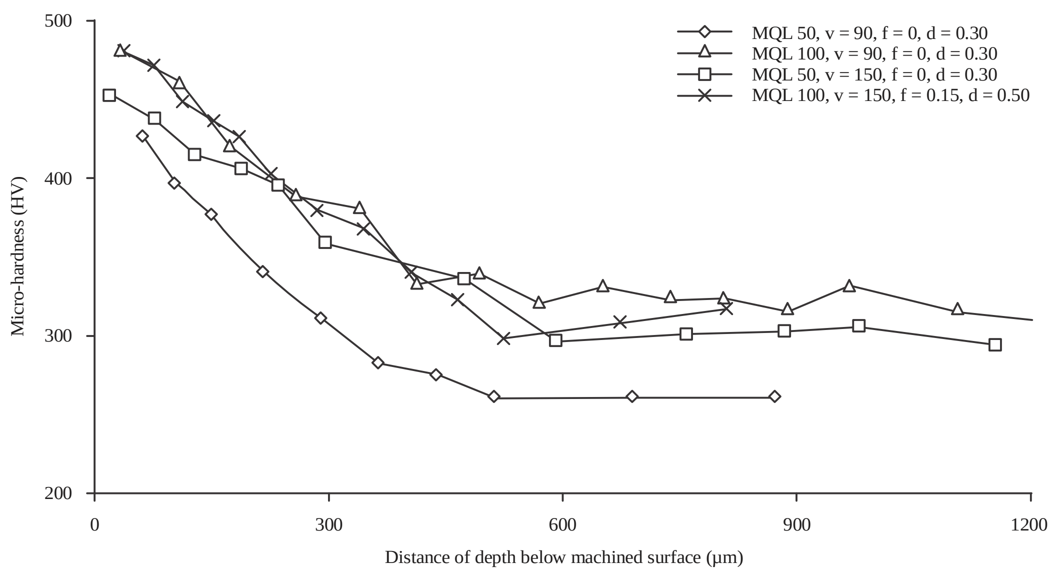

Fig. 8: Micro-hardness at cutting speed of 90 and 150 m min^{-1} with MQL 50 and 100 mL h^{-1} conditions

into high work hardening for MQL 100 mL h^{-1} conditions. The results of micro-hardness between dry and MQL 50 mL h^{-1} are quite similar at 444 and 440 HV, respectively. Pusavec *et al.*[13] also reported similar result when they claimed that cooler cutting condition gives much higher micro-hardness value.

Effect of cutting speed on the work hardening is shown in Fig. 8 where subsurface micro-hardness comparison between 90 and 150 m min^{-1} are made for MQL 50 and 100 mL h^{-1}. It is clearly shown in Fig. 8 that higher hardness values are obtained at higher cutting speed and a lower hardness values are obtained are lower cutting speed for MQL 50 mL h^{-1}, however, for MQL 100 mL h^{-1}, the effect was not obvious. Figure 8 also shows that the work hardening of MQL 100 mL h^{-1} for both cutting speed and for MQL 50 mL h^{-1} at 150 m min^{-1} are very similar which gives impression that the cutting conditions at the cutting zone at quite comparable. Figure 9 shows the effect of feed rate and depth of cut on the micro-hardness of Inconel 718 under dry condition at 90 m min^{-1}. All four experiments show quite similar trends with no major differences in micro-hardness reading. This situation may be due to low cutting speed. At high speed, the difference is more apparent, as shown

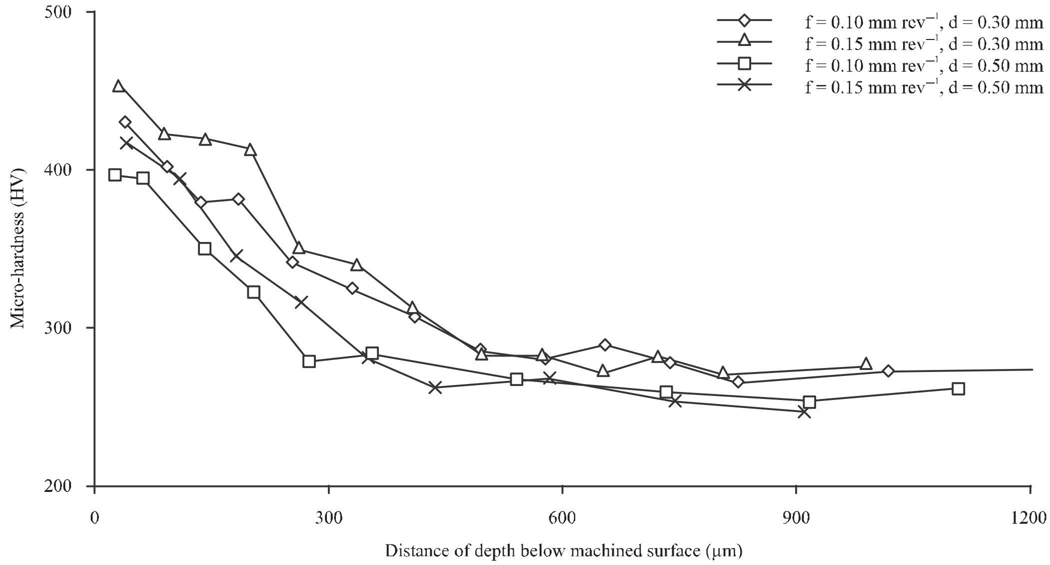

Fig. 9: Micro-hardness at cutting speed of 90 m min^{-1} with dry condition

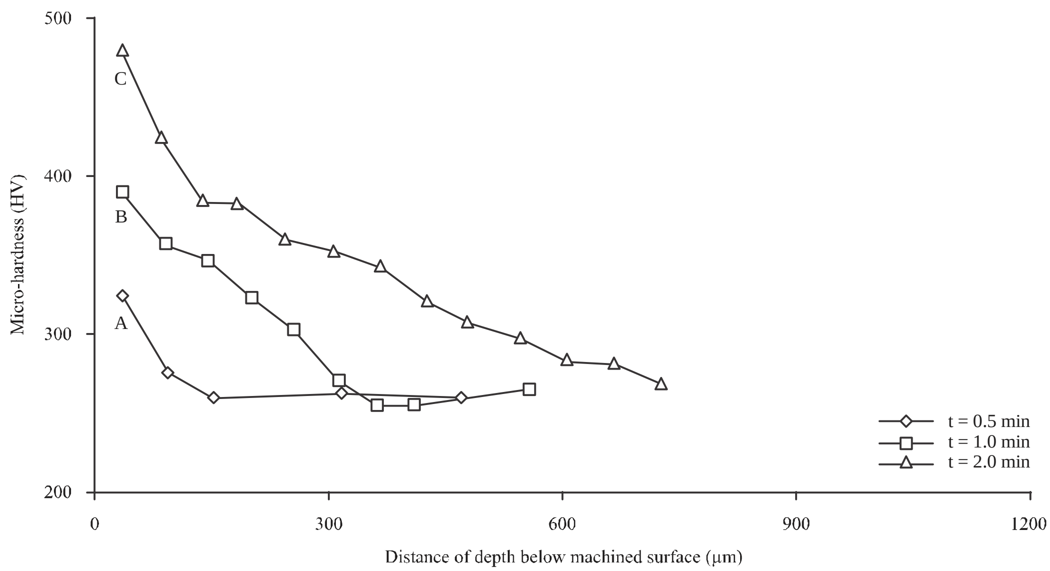

Fig. 10: Micro-hardness at cutting speed of 150 m min^{-1} with dry condition

in Fig. 8. However, close examination on Fig. 9 shows that higher feed rate and lower depth of cut resulted in higher micro-hardness values.

In all the experiments the highest micro-hardness was measured close to the machined surface layer and decreases towards the bulk micro-hardness as the depth increases. The bulk micro-hardness of the material was obtained nearer to the machined surface by the sample from lower cutting speed whereas higher cutting speed sample obtained the bulk hardness value deeper away from the surface.

Figure 10 shows the effect of tool wear at different cutting time on the micro-hardness of the subsurface samples under dry condition at 150 m min^{-1} in with a feed rate of 0.15 mm rev^{-1} and 0.50 mm depth of cut. In this experiment, the cutting will continue until the end of the specified time that is at t = 0.50 min, t = 1.0 min and t = 2.0 min. Observations made from Fig. 10 give indication that cutting time and tool wear had an impact on the work hardening of Inconel 718. Short cutting time would develop small tool wear, whereas longer cutting time would develop larger tool wear. When the cutting time was short, the highest hardness reading was 390 HV with an increase of 16% from the bulk. Slightly longer cutting time, sample B, resulted in an increase of 39% and at t = 2.0 min, sample C, the increase was 71%. It is also worth noting that the bulk micro-hardness was obtained earlier by sample A, at a distance of 95 µm from the machined surface. Moreover, prolonged stresses also affect the micro-hardness reading when sample C was compared with the sample of similar cutting condition in Fig. 8 where the micro-hardness of sample C is 8% higher.

Sharman *et al.*[2] in their experiments between 40 and 120 m min^{-1} with a feed rate of between 0.15 and 0.25 mm rev^{-1} and cutting depth of 0.25 mm under flood condition found that the micro-hardness increased on average by almost 14%. With blunt tool, the micro-hardness increased by almost 28%, from 375-480 HV. They also found that, with blunt tool, the initial bulk hardness was obtained deeper than the sharp tool, with a difference close to 200 µm. Their study also showed that there was a relationship between micro-hardness, cutting force, cutting speed and feed rate.

In another experiment, Pusavec *et al.*[13] studied the effectiveness of dry, MQL and cryogenic conditions at a speed of 60 m min^{-1} with a feed rate of 0.05 mm rev^{-1} and 0.63 mm depth of cut. In their study they found that the micro-hardness increases nearly 60% with a combination of cryogenic and MQL method. In their study, a combination of cryogenic and MQL method showed that the highest increased of micro-hardness was obtained by cryogenic, followed by dry and MQL method. The MQL flow rate used in their study was 120 mL h^{-1}. What interesting in their study was the micro-hardness values dropped very quickly and the bulk value was obtained at a depth of 40 µm from the surface of the workpiece under all cutting conditions. Although they had recorded a high increase of micro-hardness, they found no microstructural changes occurred in their experimental samples. They also did not find any evidence of thermal softening.

Substantial increase in micro-hardness recorded in this study when compared with the study of Sharman *et al.*[2] is because the material used by them had undergone prior hardening process. The distance from the surface for reaching the bulk micro- hardness in their study was also slightly deeper than the depth obtained by Pusavec *et al.*[13] which is at a distance of 40 µm. This is because apart from using new tools on every cutting, the cutting length conducted by them was shorter, at only 20 mm in length. Devillez *et al.*[17] in a turning experiment of Inconel 718 under dry and flood conditions at a cutting speed between 40 and 80 m min^{-1}, with a feed rate of 0.10 mm rev^{-1} and cutting depth of 0.50 mm observed an increase of 22 and 19% in micro-hardness. They also concluded that there were no major differences between dry and flood conditions and both conditions reaching the bulk micro-hardness at a depth of around 300 µm. Although there are numerous differences in the results obtained, all of these studies confirmed that work hardening of Inconel 718 has occurred and the rate of hardening depends on the strain hardening properties of the early process, machining parameters such as cutting speed and most important is the condition of heat generation and stress in the cutting zone[17].

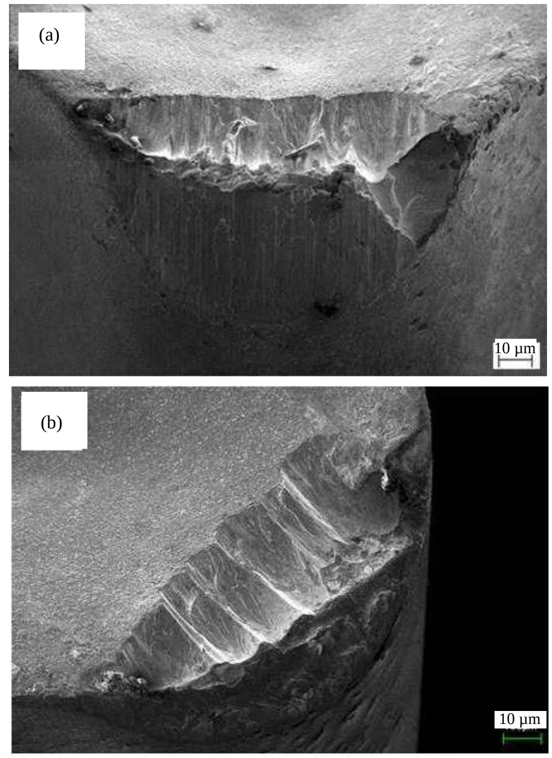

Fig. 11(a-b): Flank and crater wear at cutting speed of 150 m min^{-1}, feed rate of 0.15 mm rev^{-1}, depth of cut 0.50 mm, (a) At t = 2.0 min (continuous) and (b) At end of life (interrupted)

Figure 11 compares tool wear of sample C and the tool wear from the sample of similar cutting condition from Fig. 9. Wear from sample C apparently look worse than the wear from the sample of Fig. 9 because prolonged cutting put continuous pressure on the tool. Pawade *et al.*[18] also report that cutting condition affects work hardening behaviour of Inconel 718 in their research study using various cutting tool.

The changes in the subsurface micro-hardness is due to localization of extreme heating and stress during the machining process[10]. Thakur *et al.*[19] claimed that the plastic deformation of the machined surface causes high density dislocation that resulted in work hardening of Inconel 718. High heat generation during the cutting process causes thermal softening to occur and creates a condition where the

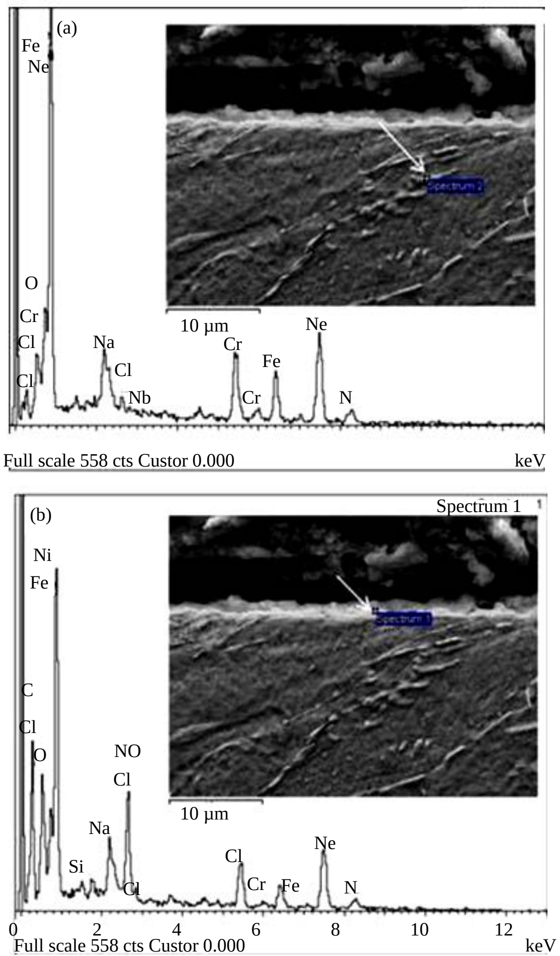

Fig. 12(a-b): EDAX profile showing presence of Nb on the (a) Grain boundaries and (b) Machined surface

machined surface expanding and tensile stresses occur. The closest layer to the machined surface, as a result of extreme heat stress from machining and rubbing effect between the tool and material, losses it durability and toughness. When heat is absorbed into the lower layers, contraction occurs in the upper layers and causes compressive stress. At the same time, extreme mechanical stress from high speed cutting creates compressive stress[16]. The effect of the trapped compressive stress is trapped in the subsurface layer and remains there and thus causes the increase in hardness of the material.

Inconel 718 containing hard carbide at the grain boundaries such as Ni_3Al and Ni_3Nb which easily transform to harder δ-phase at temperatures above 900°C. Extreme heat and mechanical stress alter the grain boundaries and cause grains to deform. When grain deformed, hard carbide position changed as well, causing localization of carbide on the surface layer and increased surface hardness as shown in Fig. 12.

Hardening material does not work well for the tool because it will quickly dulls the tool and shorten the tool life. But, material hardening may be required in certain applications to extend the fatigue life of the material[13].

CONCLUSION

The effects of dry and MQL conditions on subsurface characteristics when finish turning Inconel 718 using PVD coated TiAlN carbide tool at high cutting speed were evaluated where the microstructure deformation and micro-hardness for both conditions were assessed and investigated. Based on the results obtained throughout the experimental works, the following conclusions are drawn:

- The study found that there was severe plastic deformation when machining Inconel 718 at high cutting speed under both dry and MQL conditions. This plastic deformation is in the form of grain distortion in the direction of feed especially on the top layer closest to the machined surface. The impact of this distortion resulted in elongated grain from initially round-cornered shape which was very apparent at the top 10 µm from the machined surface
- At higher cutting speed of 150 m min^{-1}, the distortion effects between MQL 50 and 100 mL h^{-1} dry conditions are difficult to distinguish. However, a closer look at the grain deformations and orientations, MQL 100 mL h^{-1} shows worse microstructure changes, most probably due to similar effect of quenching when MQL fluids are sprayed into the hot workpiece at the cutting zone. Interestingly, sample from dry and MQL 50 mL h^{-1} shows comparable microstructure changes. At 120 m min^{-1}, microstructure changes of MQL 50 mL h^{-1} are less severe than that of dry condition at 90 m min^{-1}. All these observations imply that at high cutting speed, high flow rate of MQL 100 mL h^{-1} is unfavorable. At low cutting speed, MQL fluid seems to slow down effect of microstructure changes. This is evidently proven with MQL 50 mL h^{-1}. Machining conditions are also found to affect the rate of distortion with severe conditions are found in higher cutting speed, feed rate and depth of cut. Prolonged continuous cuts and dull tools also leave severe distortion effects
- This study found that in machining Inconel 718, work hardening always took place in all most all cutting conditions. Machining conditions such as cutting time, the wear of the tool, the method of working fluid and material early processing affect subsurface

micro-ardness. It was agreed that at high cutting speed there was no clear distinction of micro-hardness reading between dry and MQL 50 mL h^{-1}, however, the micro-hardness of MQL 100 mL h^{-1} was higher, indicating high strain hardening condition. With MQL 100 mL h^{-1}, the highest hardness was 480 HV, while with MQL 50 mL h^{-1} it was 440 HV and under dry condition, the micro-hardness is 444 HV

- The results of the micro-hardness also showed that the bulk micro-hardness was reached earlier using sharp tool at low cutting speed. The results of this study also show that to reduce the effects of material hardening during machining Inconel 718 is to avoid the use of a blunt tool. Blunt tool should be replaced to prevent hardening of the material deeper into the subsurface

This investigation on microstructure changes and micro-hardness gives indication that there is a possibility that MQL conditions may potentially perform better than dry conditions in term of less impact on plastic deformation and work hardening especially with the MQL 50 mL h^{-1}. The results from this experimental works show that machining under dry conditions is better than MQL 100 mL h^{-1} at high cutting speed where the work hardening are higher and the microstructural changes are more severe.

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